A Study of the Dynamics of Reflection Color, Helical Axis Orientation, and Domain Size in Cholesteric Liquid Crystal Displays

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Abstract

The relaxation from the field-induced homeotropic state to the equilibrium planar state of cholesteric liquid crystals is investigated. By using an optical retro-reflection technique, we have isolated the dynamics of the orientation and pitch of cholesteric helices, and through scattering and microscopy techniques, we have determined domain size as a function of time for various surface treatments. These three factors determine the viewing angle, color, and brightness of a display. An analysis of the significance of surface selection in cholesteric displays is presented.

Introduction

The primary obstacle to using cholesteric liquid crystals in video displays is the relaxation time from the homeotropic state to the planar state. The fundamentals of this transition have previously been investigated, and it is well established that the relaxation involves a conical relaxation to a metastable state known as transient planar, followed by a slow relaxation to the equilibrium state [1,2,3,4]. This relaxation is commonly given a characteristic time of about 200 ms [5].

Previous studies have reported extremely fast homeotropic to planar transitions in various cholesteric liquid crystal configurations [5], with relaxation times on the order of 5 or 10 ms. The transition times reported in such studies generally refer to the time for the reflected intensity from the display to rise to some percentage of the final brightness. However, the final brightness of the display is strongly dependent on the angular distribution of helical axes, the pitch of the material, and the angle from which the display is viewed. In this study, we investigate the dynamics of the pitch of the material, which determines the base color, and the helical axis distribution in the display, which influences the degree of color shift and viewing angle dependence of the pitch and brightness. Additionally, we investigate the dynamics of domain size, which is intrinsically linked with display brightness.

Experiment

Several previous papers have discussed methods of determining helical axis distributions for static cases [6,7]. Our study required us to observe such helical axis distributions with sub-millisecond time resolution. In our apparatus, collimated monochromatic light is incident on the display at an angle α from the substrate normal direction. Only light reflected directly back along the incident light direction (with an angular precision of 2.7°) is measured. Because light reflected at oblique angles from cholesteric helices is not measured in our setup, the measured reflected signal is directly related to the density of reflecting helices with axis at α from the cell normal and with pitch in the rage λ/n_e to λ/n_o. Thus, by scanning across α and the wavelength of incident light, we may determine the helical axis distribution and pitch at any time in the relaxation process. A full description of the apparatus will be published elsewhere.

In order to determine the size of domains as a function of time, scattering measurements based on the technique developed by Marusii et al [8] were employed. Additionally, domain size was determined using a strobe system and a camera with a reflecting microscope. Image processing software was used to determine the size of domains at specific times.

Cells used in this study had 5 μm cell gaps, and were filled with a mixture of Merck liquid crystal 18349 (Δn=0.27) and CB15 chiral additive, with a maximum equilibrium reflection at about 625 nm. Surface treatments included a strong homeotropic surfactant (Aldrich Octadecyltrichlorosilane, which we will refer to as "silane"), a homeotropic polyimide (Nissan 7511), an unrubbed planar polyimide (Dupont 2555) and a rubbed planar polyimide (Dupont 2555).

Experimental Results

From the measured optical response at various wavelengths for a cell, we can construct a 3-dimensional graph of reflected intensity vs. wavelength and time for the data. Figure 1 represents

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the relaxation process for a cell with a strong planar (rubbed 2555) alignment. Light was incident on the sample at an angle α = 5° from the cell normal direction. Using Snell's law, with an average index of refraction of 1.67 for the host liquid crystal, we may determine that all reflections shown in the graph represent helices tilted 3.0° ± 1.6° from the cell-normal direction

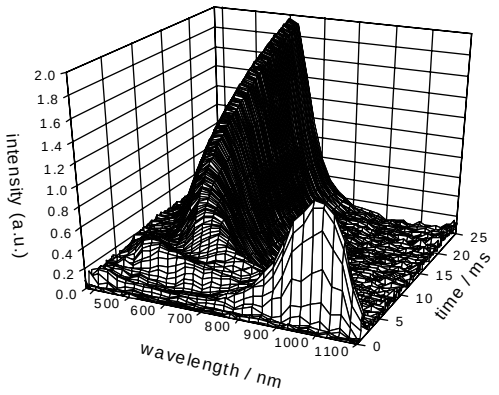

Figure 1. Retroreflection from the cell with planar alignment at α = 5°.

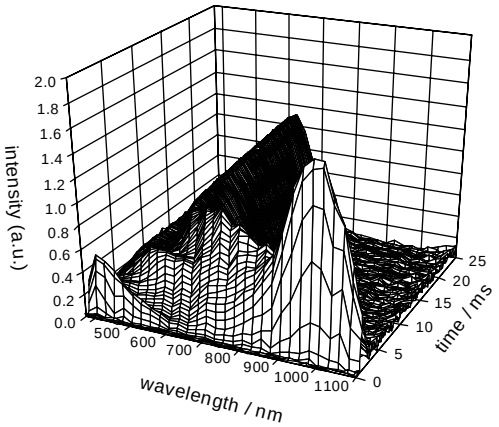

Figure 2. Retroreflection from the cell with homeotropic alignment at α = 5°.

Note that the transient planar and planar peaks are clearly apparent in this graph. The transient planar reaches its maximum reflectance at 1.3 ms, fading to zero by 3 ms. The planar reflection grows slowly, reaching its maximum by about 1 second. The reflected intensity at peak wavelength at 250 ms for this sample was 4.04 a.u. on our scale.

If we observe the silane cell, we see a somewhat different picture [Figure 2]. The reflection at 250 ms at 5° for this cell was 1.40 a.u. The other surface treatments (unrubbed 2555 and 7511) yielded results intermediate to these.

We may gain insight into this transition by looking at the reflected intensity as a function of α. Figure 3 shows reflection integrated over wavelength at various angles and times for the rubbed 2555 and silane cells. Note that the transient planar reflection at small angles is brighter than that at larger angles.

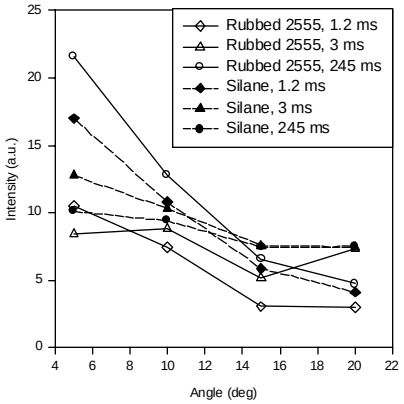

Figure 3. Intensity vs. Angle for the cells with rubbed planar alignment, silane alignment different times in the relaxation.

During the time of transition between transient planar and planar (about 3 ms), the reflected intensity takes on a wider angular distribution. The distribution for the silane cell remains somewhat peaked at small angles, while that of the rubbed 2555 cell is largely flat. In the planar state, the distribution for the silane cell remains wide, while that for the rubbed 2555 cell is again highly peaked. With increased time, the brightness for the 2555 cell continues to increase.

If we plot the wavelength of maximum reflection vs. time at α=5°, we find that the relaxation to the shortest measured pitch is completed in about 5 ms [Figure 4], independent of surface treatment.

Further observation of reflections at times up to 30 seconds demonstrates evidence of continued relaxation. In particular, we found that the helical axis distribution widened somewhat between 1 and 2 seconds for the cell with the silane surface, while the distribution gradually became more narrow (between

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1 and 20 seconds after removal of the field) for the rubbed 2555 cell. Additionally, a second pitch change occurred, which caused the reflecting wavelength to lengthen from 620 nm to about 640 nm, between 1 and 10 seconds after removal of the field. The combination of these two factors caused the reflected intensity at wavelengths longer than 620 nm to decrease somewhat before increasing again in the silane cell at small α. This effect has been reported previously without an explanation [5].

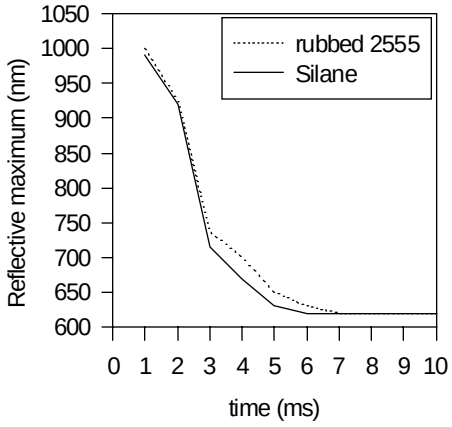

Figure 4. Change in wavelength of maximum reflection as a function of time

Our investigation of domain growth yielded interesting results. At 1.25 ms the "perfect" transient planar texture occurs with λ_{max}=975nm. After 1.25ms, small domains start to form. The density of domains reaches its maximum at approximately 4 ms and then decreases gradually.

While the relaxation process is evidently very similar during the time scale of figure 4 for both alignment layers, scattering measurements and direct observation of texture changes suggest that the relaxation to the equilibrium texture is different. For the planar cell, there is a further slow relaxation to the final planar texture, which has few defects. This relaxation is a slow process due to the slow removal of defects in the texture. For the silane alignment layer, it is seen that the defects formed at the time the equilibrium pitch was obtained are stable.

Figure 5 suggests that domains are seen to form in approximately the same way for both cells. The domain sizes calculated from scattering data agree very well with the domain size measurements obtained through microphotography and image processing (using Global Lab image software). Note that at 10 ms there are still many defects in the system for both alignment layers. By about 70 ms, the silane cell has reached its maximum domain size. The domain size of the rubbed 2555 cell continues to grow until a nearly defect-free texture is obtained, well after the time range shown in this figure.

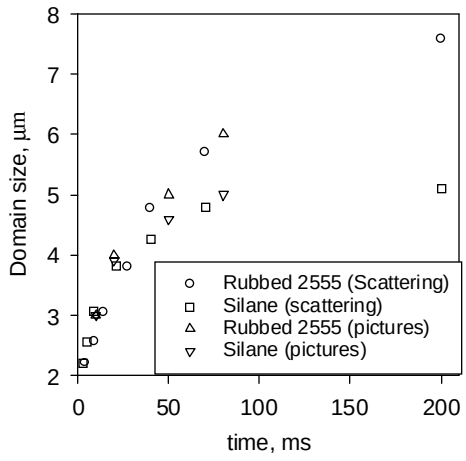

Figure 5. Change in domain size as a function of time determined using two different methods.

4. Discussion

Perhaps the most surprising point observed in the relaxation processes is the fact that the shortest (bluest color) pitch is obtained in only 5 ms independent of surface. However, maximum brightness does not occur until a time more than an order of magnitude greater has passed. This suggests that the majority of the relaxation time is not occupied by pitch relaxation, but rather by helical axis re-orientation and domain growth. After reaching this minimum pitch value, the pitch slowly lengthens, shifting the color back toward red.

We can divide the relaxation process into four stages. First, a delay time, when the homeotropic structure is still present in the cells. Second, a fast relaxation period, when the transient planar structure is formed. Third, when the equilibrium pitch is reached. Finally, a period of slow relaxation, when the planar structure is formed. Structural changes are represented schematically in Fig.6. Initially the liquid crystal goes from the homeotropic through an intermediate conic structure to the quasi-equilibrium transient planar state by changing the polar angle of director orientation (angle between director and normal to the cell

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surface) from 0 to $\pi/2$, at about 1.25ms. For both surface alignment layers this is defect-free relaxation and occurs very fast.

After the transient planar pitch is reached and the quasi-equilibrium transient planar structure in cell is formed, a subsequent twisting process is impossible without structure symmetry breaking. We observe that over the time interval from 1.25 to 4 ms, as the equilibrium pitch is being established, that a polydomain texture is formed for both surface alignment layers. We may assume a nucleation process (from 1.25 to 4ms) gives the possibility for the system to form helices with the equilibrium pitch P_o (at approximately 4-5ms). The nucleation and simultaneous twisting processes is accompanied by tilting of the helices away from the vertical position.

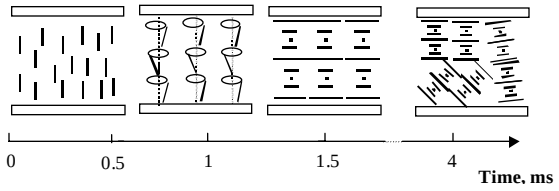

Fig.6. Schematic representation of the dynamic of structural changes in the cells.

In one regard we could say the silane cell has a faster relaxation, but our data shows that this view is misleading. The data suggests that a more accurate statement would be that the relaxation is very similar for both alignment layers up to a time of about 10ms, but the relaxation of the planar cell continues after that to a perfect planar structure, while that of the homeotropic cell does not.

It appears that the most significant difference between the relaxation processes observed for the silane cell compared to the rubbed 2555 cell is the stability of the very wide helical axis distribution of the silane cell. This causes the structure to be much dimmer when viewed on axis.

Conclusions

We must be careful in considering the correspondence of measured relaxation times for cholesteric displays. A configuration which obtains its final brightness in 10 ms may be significantly dimmer than a configuration which takes 100 ms to relax fully, if the final state of the "fast" configuration is dim compared to the "slow" display. Comparison of absolute brightness (compared to a standard) from the display, integrated over time may be a more meaningful benchmark.

While the strongly homeotropic surface yielded a greatly reduced relaxation time for on-axis measurements, the final state to which it was relaxing was much dimmer at that angle. Observing reflected intensity at small angles and times indicates that a planar alignment will give a brighter on-axis planar state for video-rate cholesteric displays. However, the off-axis brightness with such a surface will be significantly reduced.

Additionally, it is important to consider how changes in the reflecting texture at longer time scales effect the viewing of the display. Displays with more strongly homeotropic surfaces tend to promote wide angular distributions of helical axes. After the initial relaxation, this distribution continues to widen for several seconds for such cells. For the planar cells, the distribution slowly becomes more narrow over time. Thus, for displays which are not continually refreshed, the viewer will observe a change in brightness during these several seconds. The change in pitch during the time from 10 ms to 10 s is also significant, and should be considered in display design.

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